

**COMBUSTION OF CARBONACEOUS RESIDUES ON
SPENT OIL SANDS IN A TRANSPORT REACTOR**

By

Hong Qing Tang

**A dissertation submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of**

Doctor of Philosophy

Department of Chemical and Fuels Engineering

The University of Utah

August 1995

ABSTRACT

A laboratory scale dense-phase transport reactor was designed, fabricated and constructed to study the combustion of carbonaceous residues on spent oil sands produced during the fluidized bed pyrolysis of oil sands. A wide particle-size distribution group B coked sand, $\bar{d}_p = 130 \mu\text{m}$, was used for the hydrodynamic and combustion studies.

The average minimum fluidization velocity, U_{mf} , determined during a series of fluidization and defluidization experiments, was 1.7 cm/s. The transition velocities were determined in flow regime transition studies: (a) the plug slugging transition velocity, U_{ms} , was 22 cm/s; (b) the turbulent fluidization transition velocity, U_c , was 50 cm/s; and (c) the refluxing pneumatic transport transition velocity, U_k , was 75 cm/s. Particle residence time distribution experiments indicated the average particle residence time in the reactor was approximately six minutes in the turbulent fluidization regime.

The effects of process variables on the combustion of the coked sand were investigated. Coked sand combustion experiments at different superficial gas velocities indicated that there was an preferred superficial gas velocity, approximately 60 cm/s, at which the highest coke conversion was achieved.

The results also indicated that CO production rate increased whereas CO₂ production rate decreased with increasing superficial gas velocity. Coke conversion increased with increasing combustion temperature but leveled off above 946 K.

The coke conversion increased with decreasing solids feeding rate at a fixed temperature. Coked sand combustion with oxygen enriched air as the fluidizing gas indicated that using oxygen enriched combustion gas increased the coke conversion.

Preliminary studies were conducted to evaluate the effect of gaseous swirl flow on coked sand combustion. Coke conversion increased with swirl flow at a fixed temperature and solid feed rate relative to fully developed plug flow through the reactor. It is expected that coked sand combustion could approach completion with a combination of induced swirl flow, higher combustion temperatures and oxygen enriched fluidizing gas.

TABLE OF CONTENTS

ABSTRACT	iv
LIST OF TABLES	ix
LIST OF FIGURES	xi
NOMENCLATURE	xiv
ACKNOWLEDGMENTS	xvii
CHAPTER	
1 INTRODUCTION	1
1.1 Research Objectives	7
2 LITERATURE SURVEY	9
2.1 Oil Sand Resources	9
2.2 Oil Sand Recovery Methods	10
2.2.1 In-Situ Bitumen Recovery Technologies	12
2.2.2 Surface Bitumen Recovery Methods	16
2.3 Fluidized Bed Combustion	20
2.3.1 Comparison of Bubbling, Circulating and Pressurized Fluidized Bed Combustion	22
2.3.2 Innovative Designs of FBC	36
2.4 Fluidized Bed Incineration	38
2.5 Combustion Kinetics of Coke/Char on Spent Shale/Sand	48
3 EXPERIMENTAL APPARATUS AND PROCEDURES	52
3.1 Coked Sand Feeder Design, Construction and Calibration	52
3.2 Reactor Design and Construction	64

3.2.1	Reactor Body	64
3.2.2	Gas Distributor	65
3.2.3	Heating and Ignition Furnace.....	65
3.3	Air Supply and Preheating.....	68
3.3.1	Mass Flow Control	73
3.3.2	Air Preheating	74
3.4	Gas - Solid Separation	74
3.5	Process Monitoring and Control.....	77
3.5.1	Temperature Monitoring and Control.....	77
3.5.2	Pressure Data Logging	78
3.5.3	Mass Flow Rate Data Logging	81
3.6	Combustion Experiment Operating Procedures	86
3.7	Product Sampling and Analysis.....	95
3.7.1	Flue Gas Sampling and Analysis.....	95
3.7.2	Burnt Sand Sampling and Analysis	100
3.8	Material Balance Calculations.....	104
4	RESULTS AND DISCUSSION.....	107
4.1	Solid Feed Material Preparation.....	107
4.2	Hydrodynamic Studies.....	108
4.2.1	Fluidization and Defluidization	112
4.2.2	Flow Regime Transition Studies	123
4.2.3	Particle Residence Time Distribution Studies	141
4.3	Combustion Studies	153
4.3.1	Effect of Superficial Velocity on Coked Sand Combustion.....	154
4.3.2	Effect of Combustion Temperature on Coked Sand Combustion.....	165
4.3.3	Effect of Solids Feeding Rate on Coked Sand Combustion.....	171
4.3.4	Effect of O ₂ Concentration on Coked Sand Combustion.....	171
4.3.5	Effect of Swirling Flow on Coked Sand Combustion.....	175
4.4	Carbon Balances in the Laboratory-Scale Fluidized Bed Combustion Reactor	180
5	CONCLUSIONS.....	183

APPENDICES

A	TRANSPORT FLUIDIZED BED REACTOR DESIGN CALCULATIONS	187
B	THERMAL CONDUCTIVITY DETECTOR RESPONSE FACTOR DETERMINATION	197
C	EVALUATION OF COKE ANALYSIS DATA.....	207
D	EXPERIMENTAL DATA FOR COKED SAND COMBUSTION RUNS	212
	REFERENCES	213
	VITA.....	227

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1. Typical Coked Sand Elemental Analyses	6
2. Estimated Oil Sand Resources of Utah	11
3. Specifications of the Heating Elements	68
4. Mass Flow Controller Calibration	73
5. Sieve Analyses of Coked Sand Screened Through a Number 18 Sieve	109
6. Coke Conversion as a Function of Superficial Gas Velocity at a Fixed Combustion Temperature and Solids Feeding Rate	155
7. Coke Conversion as a Function of Solids Feeding Rate at a Fixed Superficial Gas Velocity and Combustion Temperature	172
8. Effect of O ₂ Enrichment and Temperature on Coked Sand Combustion	174
9. Effect of Swirl on Coke Conversion	181
B1. Composition of the Standard Gas	198
B2. GC Analytical Results for a Standard Gas Using Local Integrator	199
B3. GC Analytical Results for a Standard Gas Using HP Integrator	200
B4. Response Factor Calculation for Scotty Standard Gas	202
B5. Composition of the Certified Calibration Gas	202

B6. GC Analytical Results of Scotty Certified Calibration Gas at Low Detector Sensitivity with HP Integrator.....	204
B7. GC Analytical Results of Scotty Certified Calibration Gas at High Detector Sensitivity with HP Integrator	205
B8. Response Factor Calculation for Scotty Certified Calibration Gas	206
C1. Coke Content Determined by Muffle Furnace Combustion.....	208
C2. Summary of t-test Results	210

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Oil Sand Bitumen Recovery Schemes	5
2. Fluidization Regimes Employed in Fluidized Bed Reactors.....	24
3. Bubbling Fluidized Bed Reactor.....	26
4. Circulating Fluidized Bed Reactor.....	29
5. Pressurized Fluidized Bed Combustion Reactor.....	32
6. Bubbling Fluidized Bed Incinerator	42
7. Circulating Fluidized Bed Incinerator	45
8. Schematic of Experimental Apparatus.....	54
9. Schematic of the Solids Feeder.....	56
10. Cumulative Weight Fed versus Feeding Time at Various Controller Settings	59
11. Feeding Rate versus Feeding Time at Various Speed Controller Settings.....	61
12. Average Feeding Rate versus Feeder Controller Settings	63
13. Schematic of the Reactor.....	67
14. Wiring Diagram of Heating Elements	70
15. Flow Diagram of Air Supply System	72

16. Dual Cyclone Solids Separation System	76
17. Typical Temperature Profile	80
18. Schematic of Pressure Data Logger Configuration.....	83
19. Calibration of the Pressure Transducer.....	85
20. Schematic of Mass Flow Rate Data Logging System	88
21. Mass Flow Rate Calibration	90
22. Typical Output from Mass Flow Rate Data Logging	92
23. Schematic of the Flue Gas Sampling System	97
24. TGA Analysis of Coked Sand	103
25. Coked Sand Average Particle Size Distribution	111
26. Typical Fluidization and Defluidization Curves for Multisized Particles	114
27. Fluidization and Defluidization Pressure Drop versus Superficial Air Velocity for Multisized Coked Sands ($H/D=2.5$).....	117
28. Fluidization and Defluidization Pressure Drop versus Superficial Air Velocity for Multisized Coked Sands ($H/D=3.5$).....	119
29. Fluidization Pressure Drop versus Superficial Air Velocity for Multisized Coked Sands	121
30. Typical Flow Regimes Observed in Gas-Solid Fluidized Beds	125
31. Pressure Drop versus Operation Time and Superficial Air Velocity.....	132
32. Standard Deviation for Pressure Drop versus Superficial Air Velocity.....	134
33. Standard Deviation for Pressure Drop versus Superficial Velocity at Different Temperatures	137

34. Typical Particle Residence Time Distribution Curves in a Fluidized Bed with Constant Solids Feed	144
35. Tracer Concentration versus Solid Particle Residence Time	147
36. Comparison of the Tracer and Coked Sand Particle Size Distributions	149
37. Tracer Concentration versus Residence Time with KMnO_4 and KMnO_4 Coated Sand Tracers	151
38. Coke Conversion versus Superficial Gas Velocity	157
39. CO and CO_2 Concentrations versus Superficial Gas Velocity	160
40. CO and CO_2 Production Rate versus Superficial Gas Velocity	162
41. Coke Conversion versus Combustion Temperature	167
42. Test for the Kinetics of Coked Sand Combustion	170
43. Schematic of the Swirl Blade Configuration	177
44. Swirl Blade Position in the Reactor	179